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Simulation of Soil Erosion Induced by Human Trampling

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Previous work on soil erosion induced by human trampling has concentrated on damage to the vegetation cover to the virtual exclusion of studies on the mechanics of the processes involved and the measurement of soil loss and run-off. As a contribution towards rectifying these deficiencies, a laboratory study was carried out to assess the nature of the forces involved in trampling, and to measure run-off and soil loss from sloping vegetated surfaces under controlled conditions of trampling and simulated rainfall. The results show that most damage to vegetation by walking arises from compaction by the heel in the early part of each step and shearing by the toe action at the end of each step. The shearing action is the most important, and, within the 5° to 20° range of slopes studied, has its greatest effect on the steeper slopes. The breakdown of the soil by trampling occurs whilst wear of vegetation is still in progress, and not, as previously thought, after the vegetation cover has disappeared. Thus, by the time there is visual evidence of declining plant cover, the critical period in which erosion is initiated is already past.

Keywords: soil erosion, human trampling.

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1. Introduction

Although soil erosion as a result of the removal of the vegetation cover by human trampling has been reported in many recreational areas (Bayfield, 1971, 1973; Liddle, 1975; Coleman, 1977), few attempts have been made to understand the mechanics of the trampling processes involved. In some studies, the forces of trampling have been simulated by using rollers or dropped weights, but these techniques are criticised by Liddle (1973) as producing conditions widely different from reality. Further, with their emphasis on wear of vegetation and, therefore, on damage to the ecological environment, these experiments have included few measurements of soil loss, and are, at best, only indirectly related to erosion. This study goes some way towards rectifying this deficiency by, first, assessing the forces involved in trampling on sloping surfaces, and, second, by measuring run-off and soil loss from sloping vegetated plots under controlled laboratory conditions of trampling and simulated rainfall. In discussing the results of the study, particular attention is paid to the relationships between soil loss, run-off, trampling forces and wear of vegetation, and the way in which these effects change with increasing slope angle.

2. Force measurements

2.1. EXPERIMENTAL SET-UP

The experimental set-up comprised a plywood box, 600 mm long, 400 mm wide and 410 mm high, with a platform hinged at one end and supported at the other by being bolted to two metal bars, fixed to and extending upright from the side of the box (Figure 1). Using a series of equidistant holes in the bars, the platform could be set at slope angles of 4·3°, 7·4°, 10·5°, 13·6°, 16·8°, 19·9°, 23·4°, 26·5°, 29·8° and 36·5°. The box was placed on top of a force platform which consisted of a suspended steel plate with piezo-electric crystal sensors located at the four corner supports. The sensors were calibrated to give electrical signals, proportional to the forces applied in three orthogonal directions, and these signals were relayed to a recorder–amplifier and represented as three wave traces on u.v. sensitive paper. An approach ramp and exit platform were constructed by using a ladder and a table.

The first-named author formed a test subject of 80 kg weight, equivalent to a force of 785 N. Tests were made walking uphill at normal speed with the subject wearing

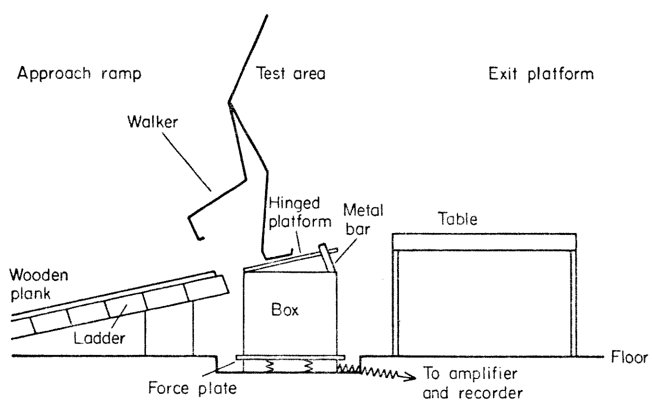

Figure 1. Apparatus for force measurement on sloping surfaces.

tennis shoes to ensure a good grip on the surface of the platform and flexibility of foot movement. At least two replications were made for each slope angle. Guide marks were placed on the approach ramp so that the right foot always landed close to the centre of the platform. Photographs were taken of one test run at each angle to show the attitude of the foot whilst walking.

2.2. RESULTS AND ANALYSIS

Typical records of the vertical (*Fz*), horizontal (*Fy*) and lateral (*Fx*) force components during one footstep are presented in Figure 2.

The trace of the vertical force with time shows two distinct peaks and a trough. The first peak, at 0·10–0·25 sec after initial contact between the foot and the plate, occurs, according to the photographic evidence, when the body of the subject rises to its maximum height over a static foot. The centre of gravity of the body accelerates upwards by an extension at the knee and hip joints, and this acceleration is accompanied by a vertically upward thrust from the force plate. This vertical thrust is, by Newton's second law of motion, equal to the weight of the subject plus the product of the body mass and vertical acceleration of the centre of gravity. The second peak, at 0·6–0·8 sec after initial contact, is also associated with a vertically upward acceleration of the body's centre of gravity as the body again rises prior to the leading foot making contact with the ground. The trough results from a downward acceleration of the body's centre of gravity caused by a lowering of the trunk at that stage of the step.

The horizontal force in the direction of walking (*Fy* in Figure 2) shows a negative peak (*Fya*) representing a decelerating force as the heel strikes the ground at the commencement of the stride. The horizontal force then passes through zero as the body's centre of gravity overtakes the stationary foot and finally rises to a positive peak, indicating an accelerating force, as the body is given a forward thrust before the toe of the stationary foot leaves the ground. For a large part of the step, the horizontal force is only a small proportion of the subject's body weight and rarely exceeds 150 N. The horizontal force persists for a longer time with increasing slope angle, but does not rise appreciably in magnitude.

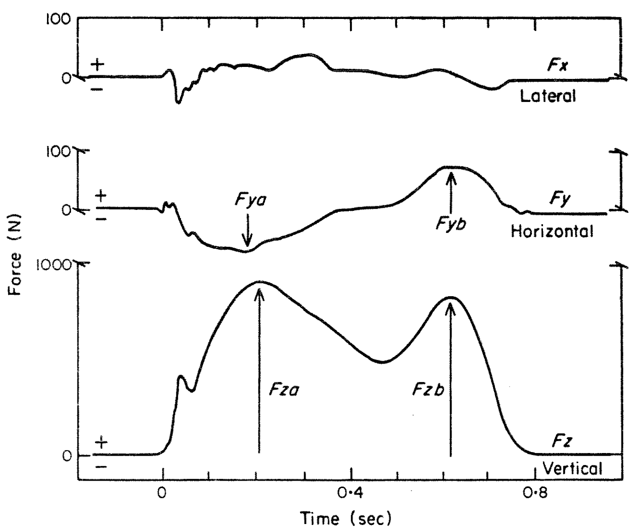

Figure 2. Typical recording traces of the force components. These traces are for a slope of 10·5°.

The lateral force component is always very small, rarely exceeding 50 N, and is ignored as a factor in the trampling process.

A series of force platform records was obtained, one set for each slope angle. In order to condense these complex data, it was decided that only the peak values of *Fy* and *Fz* would be considered, and that the transverse force, *Fx*, would be neglected. In Figure 2, the peaks *Fya* and *Fza* occur almost simultaneously; similarly, the later peaks *Fyb* and *Fzb* occur close together. Such near coincidences were found in tests at all slope angles.

To study the effects of foot action on the ground, it is helpful to calculate the components of force normal and tangential to the slope, rather than to work with the vertical and horizontal forces recorded directly by the force platform. Figure 3 shows the relationships between the forces. The coincident peak values *Fya* and *Fza* provide the maximum values *Ra* and *Va* of the compressive (normal) force and the upslope shear (tangential) force. The later coincident peaks, *Fyb*, *Fzb*, provide a second pair of maximum values, *Rb* and *Vb*, the shearing force *Vb* now being in the downslope direction. Similar calculations at all slope angles provide the data plotted in Figure 4.

The peak compressive (normal) forces, *Ra*, *Rb*, decrease by about 200 N over the range of slopes used in the test, while the shear (tangential) forces, *Va* and *Vb*, increase by as much as 400 N over the same range of slopes (Figure 4). The shear force values tend to become constant as the slope angle is increased beyond about 26°. At the steeper slopes, the method of ascent is changing from normal walking to a form of climbing with a different foot action.

From the compressive and shear forces, the associated shear stress intensities may be obtained by dividing the force by the area of the foot in contact with the platform (Harper *et al.*, 1967). Although it was not possible to make direct measurements of the latter in this experiment, it is clear from general observations and photographic evidence that the compressive stress is high at the beginning of each step, as the heel carries the compressive load on a small contact area. As the whole of the foot comes into contact with the platform later in the step, the compressive stress falls, but there is a final rise as the toe pushes off at the end of the step. In general, the compressive stress has its maximum value at the "heel-strike" stage of the step.

The shear stress follows a pattern similar to that of the compressive stress, but reaches a maximum value at the "toe-off" stage, as the foot prepares to leave the platform.

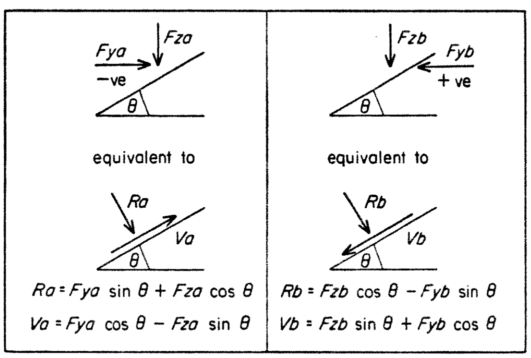

Figure 3. Forces involved in trampling. *Fya, Fza, Fyb, Fzb*—peak values of horizontal and vertical foot forces recorded by force platform (Figure 2). *Ra*—maximum compressive force associated with upslope shearing action. *Va*—maximum upslope shear force. *Rb*—maximum compressive force associated with downslope shearing action. *Vb*—maximum downslope shear force.

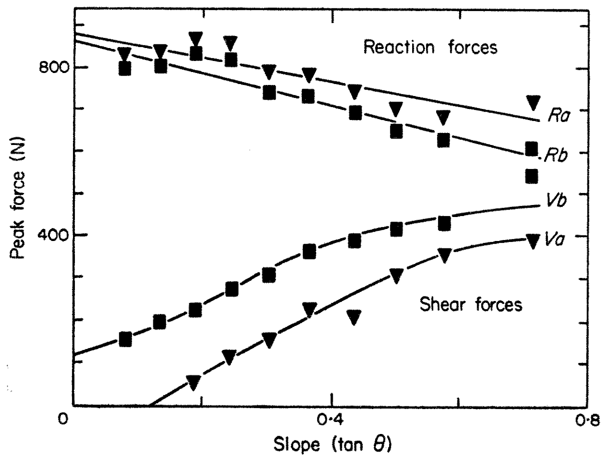

Figure 4. Relationship between forces and slope angle.

It is to be expected, therefore, that damage to vegetation and soil by compaction will be greatest in the early part of each step, and results from the action of the heel. The damage due to shear, however, will be greatest at the end of each step, and is associated with the action of the toe. In view of the force magnitudes established, it appears that the shearing action of the foot contributes far more to vegetation wear and footpath damage than does its compressive action. The shearing action causes some direct downslope displacement of soil, but its major significance is in the loosening of soil particles and their detachment from the soil mass, preparing them for removal by overland flow.

3. Trampling and overland flow experiment

3.1. EXPERIMENTAL SET-UP

A laboratory experiment was designed to measure soil loss from grass plots, $1\cdot2\times0\cdot6$ m, set at slope angles of 5°, 10°, 15°, 20° and 30°, under controlled conditions of trampling and simulated rainfall. The rainfall simulator, a modified version of that described in D'Souza and Morgan (1976) as producing acceptable characteristics of kinetic energy and drop-size distribution, extended to give spray from five nozzles over an area 5×3 m, yielded rainfall at an intensity of 500 mm/h with values of 94–97% for the Christianson spatial uniformity coefficient. The rain was applied for five minutes, giving a fall of 41·7 mm. Although such a storm is unrealistic for British conditions, it represents a magnitude–duration combination which is not uncommon world-wide (Rodda, 1970).

The plots were made of wooden boxes, partially filled with a sandy loam soil of the Cottenham Series (King, 1969) and covered with turfs taken from the grounds of the National College of Agricultural Engineering to give a surface flush with the top of each box. The plots were left untouched for seven weeks to allow the soil to settle and the turfs to matt. The plots were fixed on scaffolding under the simulator to form a pathway of increasing slope which could be walked. A step-ladder was placed at the top end and hand rails erected for safety as the path became slippery and dangerous when wet. Soil loss and run-off were collected at the downslope end of each plot using

Gerlach troughs with connecting hoses feeding into 12-l capacity water bottles (Morgan, 1977).

The experiment consisted of alternately trampling the plot and spraying it with rain. Trampling was carried out in both upslope and downslope directions with two footsteps per plot on the ascent and three on the descent. The leading foot was changed every 25 tramples for both upward and downward walking to give as even wear as possible over the plots. The first storm was applied to the plots in their untrampled condition, and successive storms after 50, 100, 150, 250, 400, 550, 700 and 900 tramples, thereby giving eight events of 50, 50, 50, 100, 150, 150, 150 and 200 tramples respectively. No further trampling was carried out because, after 900 tramples, the micro-relief on the plots showed pronounced step formation and a roughness that was unrealistic in relation to the plot size and the scale of the experiment. The first-named author trampled the plots wearing Wellington boots, as these gave the best grip on the wet surface. Antecedent soil moisture was determined on three plots prior to each trampling event, using nylon-electrical resistance blocks, previously calibrated in the laboratory, located between 5 and 10 cm below the surface. Between each storm and the next trampling event, the plots were covered with polythene sheeting to keep out natural rain and allowed to drain for 24 h. An attempt was made to assess the compaction resulting from trampling by using a cone penetrometer to measure soil resistance at three points on each plot after each trampling event. The readings are in arbitrary units and meaningful for comparative purposes only.

3.2. RESULTS

The soil moisture readings remained relatively constant but, at around 45%, rather high for the duration of the experiment. Thus, each trampling and storm event occurred under similar antecedent moisture conditions approaching field capacity. The relationship between penetration resistance and trampling (Figure 5) is erratic, but with a trend towards decreasing resistance with increasing trampling. Run-off increases rapidly from 0–50 tramples on all except the 30° slope (Figure 6), and then levels off between 50 and

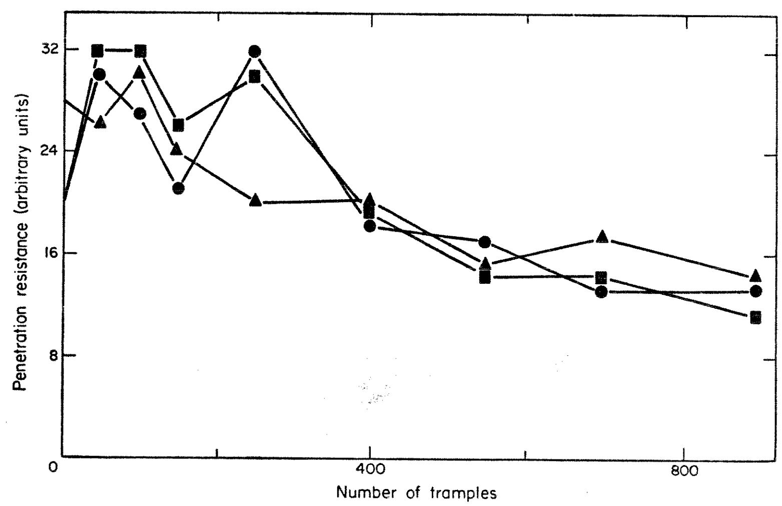

Figure 5. Relationship between penetration resistance and number of tramples. Slope: ▲—▲, 30°; ■—■, 15°; ●—●, 5°.

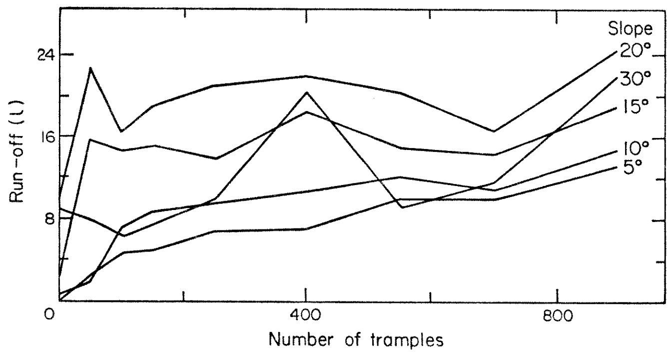

Figure 6. Relationship between run-off and number of tramples.

700 tramples in spite of increasing vegetation wear. It increases again between 700 and 900 tramples. Run-off volumes increase, as expected, with slope steepness.

Soil loss from each storm increases with greater trampling (Figure 7) and slope steepness (Figure 8). The increase with trampling pressure follows a linear function, but the

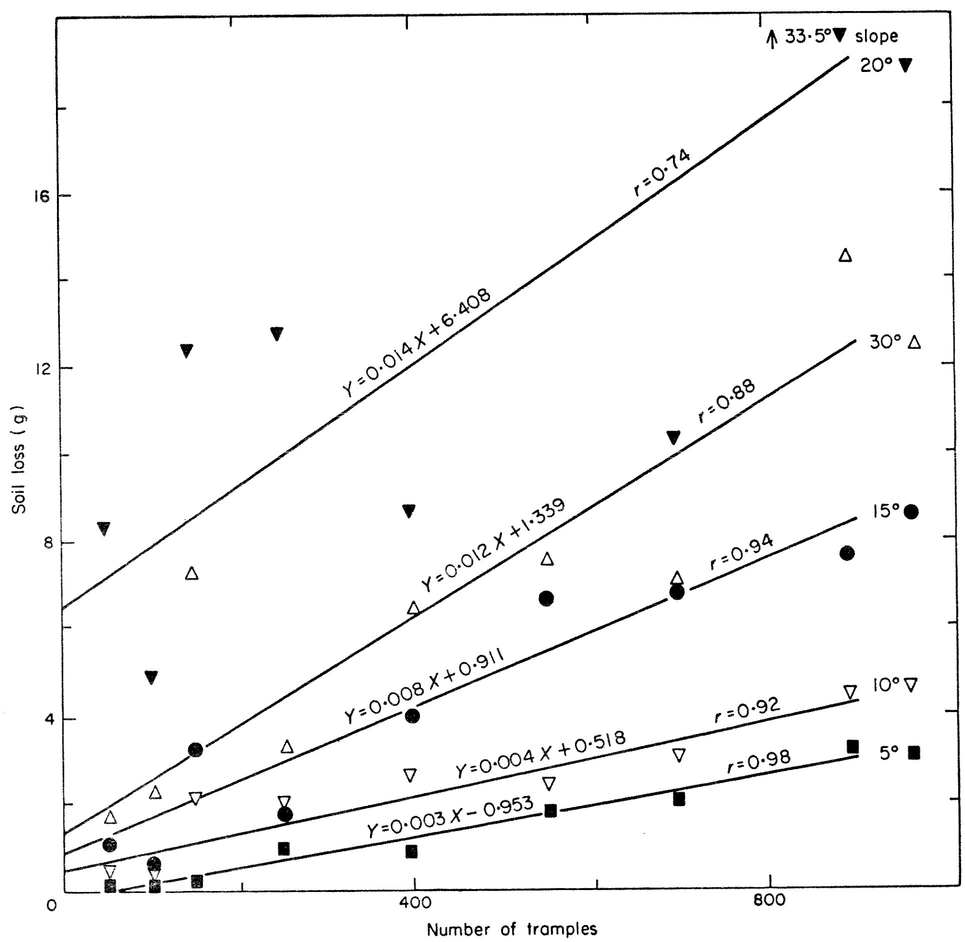

Figure 7. Relationship between soil loss and number of tramples.

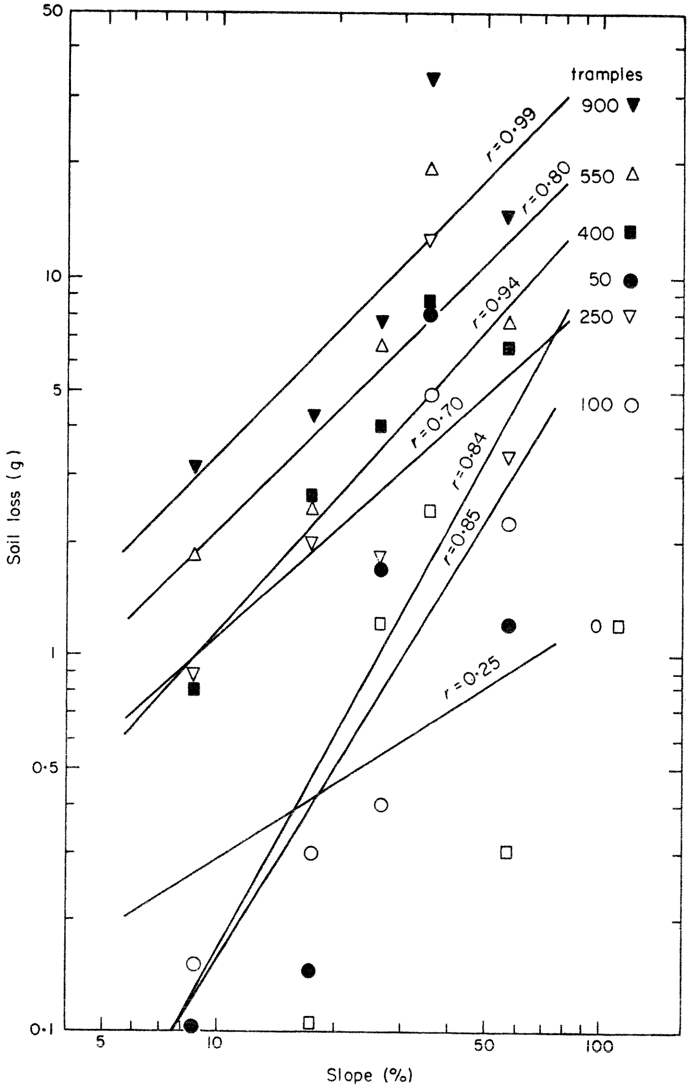

Figure 8. Relationship between soil loss and slope angle.

increase with slope steepness is best approximated by a power function. The values of the exponents in the power function increase rapidly from 0–50 tramples, remain high between 50 and 100 tramples but, at greater trampling pressure, fall to a constant value, but one which is higher than that for the untrampled condition (Table 1).

3.3. DISCUSSION

The increase in run-off in the early stages of trampling is expected because of decreasing infiltration following an increase in compaction of the soil. The levelling-off in run-off volumes after 50 tramples results from increased depression storage as the footmarks on the plots deepen and the surface is worn into steps. Overall, however, the relationship between run-off and compaction is poor and probably reflects the decrease in compaction

TABLE 1. Values of m in the empirical relationship between soil loss (E), and slope percentage (S), in the form $E = kS^m$

Number of tramples	Value of m
0	0·70
50	1·90
100	1·73
250	0·96
400	1·21
550	1·06
900	1·08

with increasing trampling pressure. This is contrary to what was anticipated (Liddle, 1973) but may be associated with the soil moisture being close to field capacity as a result of limited drainage through the wooden base of the plots. Under this condition, it is possible that gradual increases in pore water pressure in the soil counteract the effect of compaction.

The increase in soil loss with trampling pressure is more marked on the steeper slopes, as witnessed by the higher values of the regression coefficients. This trend holds for slopes up to 20°, but the gradient of the regression line decreases on the 30° slope, a change which may be associated with the flattening out of the shear force component of trampling during the transition from walking to climbing.

The values of the exponents in the power function relating soil loss to slope steepness are lower than the value of 1·4 obtained by Zingg (1940) and commonly used in predictive models of erosion (Kirkby, 1971; Ahnert, 1977), except at 50 and 100 tramples. They compare well, however, with those obtained in similar laboratory experiments on small plots (Horvath and Erödi, 1962; D'Souza and Morgan, 1976). The pattern of changing values in the exponent (Table 1) may be explained by an initial response to trampling on the vegetation cover, resulting in unstable conditions, with increased run-off and accelerated rates of erosion, followed by an adjustment to the new conditions, indicated by the almost constant value of the exponent even though trampling continues to occur and soil loss is higher than on the untrampled plot. This pattern, however, does not accord with that expected from the changes observed in the vegetation cover. Patches of bare ground do not appear until after 250 tramples, by which time much of the grass has become smeared with a layer of soil as the grass blades are forced into the soil mass and the soil is displaced downslope by the shearing action of the toe. It would appear, however, that, in spite of this visual evidence of instability, by this time, conditions are already stabilizing to the increased trampling intensity. After 900 tramples, vegetation loss is between 50 and 75% of the original cover.

4. Implications

The results of the two experiments suggest that the generally held views that accelerated soil loss does not commence until at least 30% of the ground surface is bare of vegetation (Elwell and Stocking, 1976) and that the major cause of vegetation wear is mechanical abrasion and pressure need to be re-examined. It appears that, certainly under the wet soil conditions of the second experiment, most wear results from soil deformation and smearing, and is thus related to shearing forces associated with the action of the toe in walking rather than compaction forces associated with the impact of the heel. This conclusion is borne out by the fact that, for slopes up to 20°, these effects are most marked on the steeper slopes, and that, with increasing slope steepness, shear forces become more important whilst the compressive forces decrease. Further, the loosening and breakdown of the soil occur in the early stages of trampling whilst the vegetation cover is still dense, but before there is any visual evidence of vegetation wear, suggesting that the protective effect of vegetation is less than is generally recognized. By the time vegetation wear is noticed, the critical period in which accelerated erosion is initiated has already passed, and the land is already adjusting to the new conditions of greater trampling and increased soil loss.

Even though there are many limitations to these experiments, for example the high rainfall intensity used, the restriction of the study to one soil and to a limited range of slopes, the small plot size, the use of Wellington boots as footwear, and the lack of data on the forces involved in downhill walking, the results indicate that a thorough understanding of the mechanics of trampling and the forces involved is a necessary prerequisite for designing effective strategies for soil conservation. At present, many of the assumptions on which conservation practice is based, particularly those relating soil loss to vegetation cover, appear to be unsound, Much more attention needs to be paid to the behaviour of the soil in the early stages of trampling to determine if the onset of bare ground is a response to and not, as previously believed, a symptom of unstable conditions. Future studies must also examine whether, as trampling intensities change both seasonally and from year to year, the land experiences a whole series of cycles of stability and instability on the pattern of the single cycle identified here.

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